

LS-111

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AMBIENT GROUND MOTION MEASUREMENTS AT
ARGONNE NATIONAL LABORATORY OVER EXTENDED TIME PERIODS

BACKGROUND

Successful operation of the APS facility requires a very stable particle beam. Vibration coupled through mechanical systems, such as magnet supports, beam tube supports, and other paths can cause deterioration of the particle beam. There are two sources of vibration: external, or far field, which is generated external to the APS site and internal, or near field, which is generated on site and associated with operation of the facility. Internal vibration sources can be controlled or minimized using good design practices to eliminate or reduce vibration amplitudes of machinery and equipment. Depending on their origin, external vibration sources may or may not be controllable, therefore it is necessary to have sufficient knowledge of their amplitude level and frequency content to predict any adverse effects on the operation of the APS facility.

OBJECTIVES

The primary objective of this study was to measure the far field ground vibration over long time periods to get an accurate representation of its characteristics (amplitude and frequency) for both active (weekday) and inactive (weekend) times at ANL. As a secondary objective, the instrumentation installed for the above was used to measure the response resulting from vehicular traffic on the road adjacent to one of the measurement locations.

LOCATION AND TIME

Measurements were conducted in the vicinity of Building 335 to take advantage of the proximity of the required data acquisition and processing equipment which is located in Building 335 and not portable. A layout of the measurement locations as referenced to Building 335 is shown in Fig. 1. Two

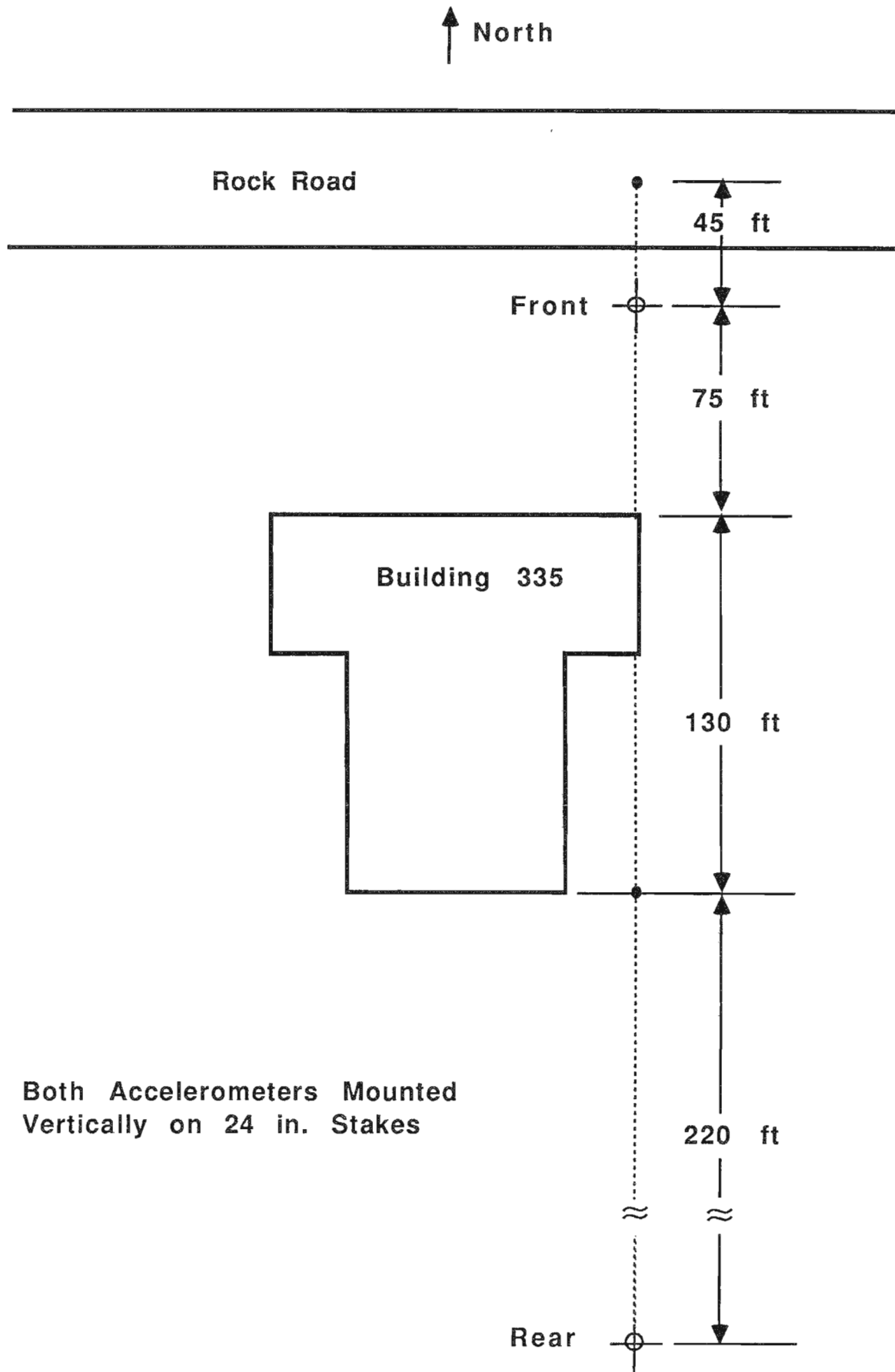


Fig. 1. Measurement site and accelerometer locations

accelerometers (PCB 393C) were mounted vertically on 24 in. long stakes, 1 in. in diameter, located 425 ft apart and in line with the east edge of the building. Designations of "front" and "rear" will be used to differentiate between measurement points throughout this report.

Data were collected November 6 to 9, 1987, and November 10 to 12, 1987, for inactive (weekend) and active (weekday) periods respectively. As a result of processing the displacement data, a 8.1 Hz periodic signal was observed. In an attempt to understand the 8.1 Hz signal, two more sets of measurements were made. A "fast cycle" set of displacements was measured with a descriptive PSD generated for each measurement point. The measurements were initiated on the afternoon of November 17, 1987, and continued to the early morning of November 18, 1987. Displacements were also continuously monitored in a real time mode for approximately 35 minutes beginning about 2:00 PM on November 20, 1987. Measurement of soil response to vehicular motion was conducted during the afternoon of November 21, 1987.

MEASUREMENT TECHNIQUES AND DATA ANALYSIS

Ground accelerations were measured with PCB 393C accelerometers and integrated using PCB 180A10 integrating amplifiers [1] to obtain displacements. The displacement signals were then coupled to a HP 5451C Fast Fourier Analyzer. A program was developed to generate a displacement-PSD, integrate the area under the curve to a preselected frequency, then print the cumulative value. For each series of 10 printouts one PSD would be stored on a hard disc for subsequent analysis of the data from both the active and inactive time periods. Each generated PSD was stored when acquiring the "fast cycle" data to eliminate the possibility of erroneous values due to scanning frequencies coinciding with the 8.1 Hz on-off time.

The real time mode of data acquisition consisted of digitizing the displacement signal and storing it sequentially on a hard disc for later analysis. Since the main objective of the real time measurement was to determine on-off times and amplitudes of the 8.1 Hz signal, only the front displacement was stored because of limited disc storage and the fact that the amplitudes measured in the front were larger.

Soil response to vehicles traveling on the road was measured simultaneously by both the "front" and "rear" transducers allowing one to calculate attenuation if the amplitudes were sufficiently large. As part of the vehicular response measurement scheme, a rectangular timing pulse was generated, its leading edge corresponding to the vehicle proximity to the "front" accelerometer. The "front" and "rear" displacements and the timing pulse are presented, all with respect to a common time axis.

DISPLACEMENT-TIME RESPONSE (INACTIVE PERIOD)

RMS displacement-time response for the weekend of November 6 to 9, 1987, with the 8.1 Hz contribution removed is shown in Fig. 2. Both displacements are approximately equal until hour 41 when the activity of the "front" displacement increases dramatically. This is attributed to deer which ate the plastic and foam covering from the accelerometer, thus exposing it to rain and wind; the period of time between hours 48-58 corresponded to a period of rain showers. After the foam and plastic was replaced, the "front" and "rear" signals were again approximately equal. No distinct increase in soil displacement can be observed between the normally more active daylight hours and the quieter night hours.

The 8.1 Hz displacement was separated from the composite displacement and its contribution is plotted in Fig. 3. Two features can be observed:

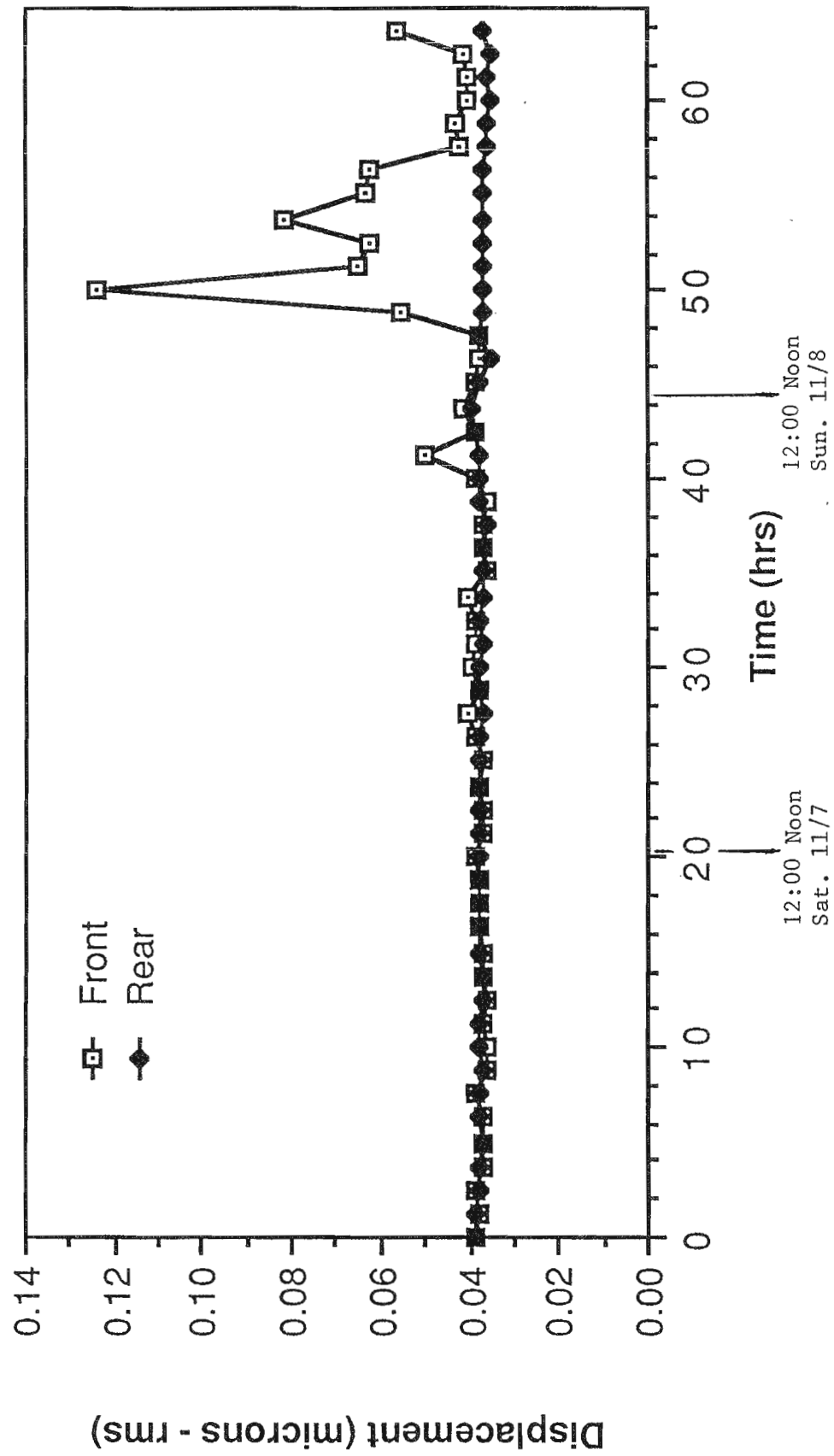


Fig. 2. RMS displacement-time response for inactive period, 8.1 Hz contribution removed

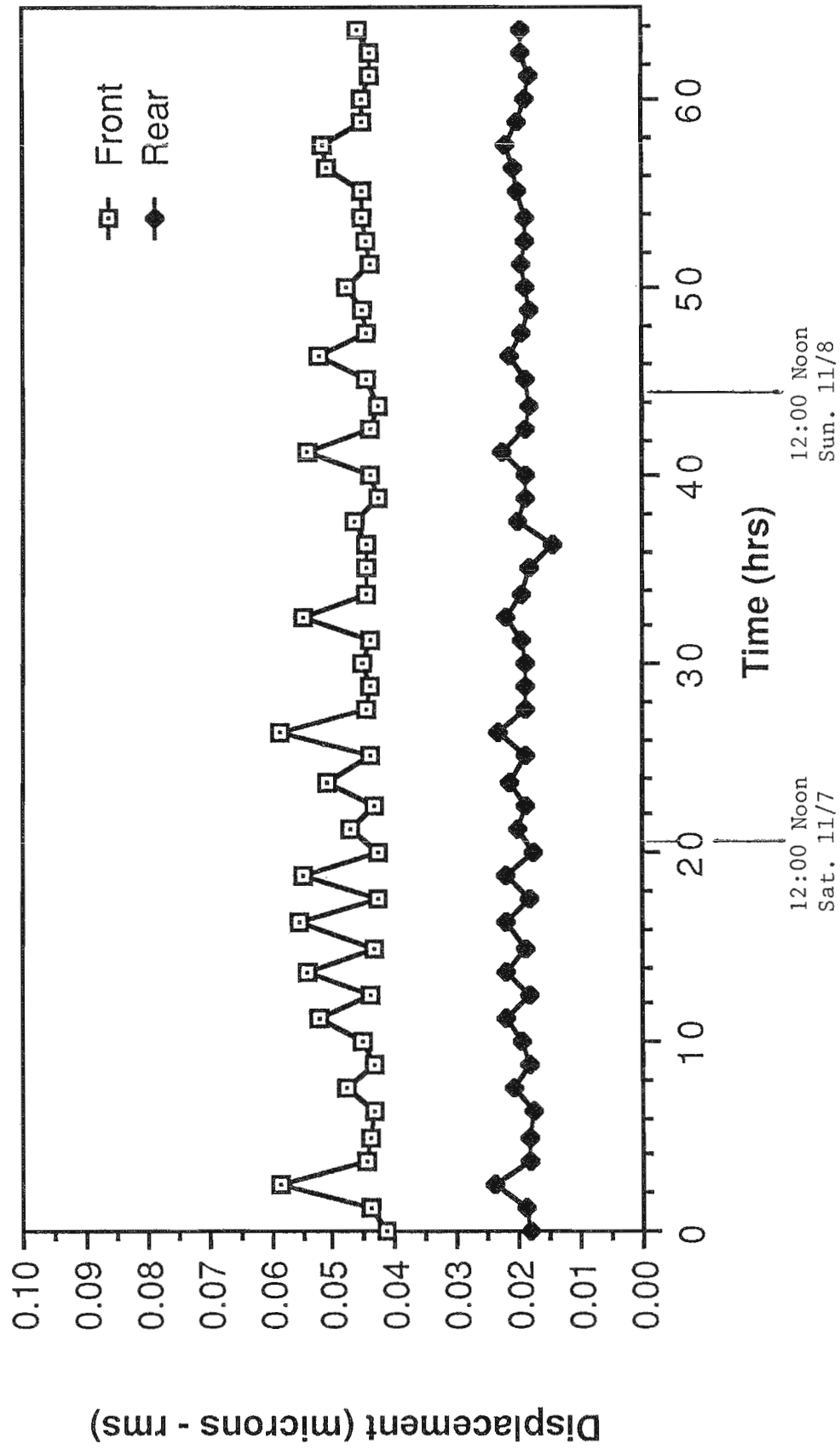


Fig. 3. RMS displacement-time response for inactive period, 8.1 Hz contribution

1) "Rear" displacement is less than one-half that of the front; 2) There are amplitude maximums on both. The approximate time between maximums is recorded in Table 1. Between 11.2 hrs - 26.7 hrs the average cycle time is about 2.75 hours.

DISPLACEMENT-TIME RESPONSE (ACTIVE PERIOD)

Figure 4 describes the total measured soil displacement time response for the active period (weekday). The "front" amplitude is larger than the "rear" with amplitude peaks again present. Since the 8.1 Hz displacement is site specific, it is digitally removed from the PSDs and the results presented in Fig. 5. "Front" and "rear" displacements are about equal except at times of maximum activity at the site, where fluctuations of the "front" are greater as it is located closer to the excitation sources (e.g., vehicular traffic on Rock Road). These larger fluctuations can be seen in greater detail in Fig. 6 in which the vertical scale has been increased. Both the "front" and rear" are equal and the lowest during 29.5 hrs - 37 hrs (\approx 10:00 PM - 5:00 AM) when site activity is at a minimum.

No periodic or cyclic displacement amplitudes, such as those of Fig. 3, can be observed in the RMS displacement time response plot of the 8.1 Hz contribution plotted in Fig. 7. However, a cyclic maximum amplitude is seen in Fig. 4. The approximate occurrence and cyclic times are presented in Table 2. A cyclic event with a period of approximately 1.6 hrs is present. However, it contains very little 8.1 Hz information. The analysis implies that the contribution to cyclic behavior is from frequencies close to 8.1 Hz.

The frequency content of the measured displacements for the active period with low and high site activity are shown in Fig. 8 and Fig. 9 respectively. The times listed on the two figures can be referenced to Fig. 5. Low

Table 1. Occurrence and Cyclic Times of 8.1 Hz Maxima
from Inactive Period Data

<u>Occurrence Time, hrs</u>	<u>Cycle Time, hrs</u>
1.3	-
7.7	6.4
11.2	3.5
14	2.8
16.5	2.5
18.8	3.3
21.3	2.5
23.8	2.5
26.7	2.9
32.6	5.9
41.4	8.8
46.8	5.4
57.2	10.4

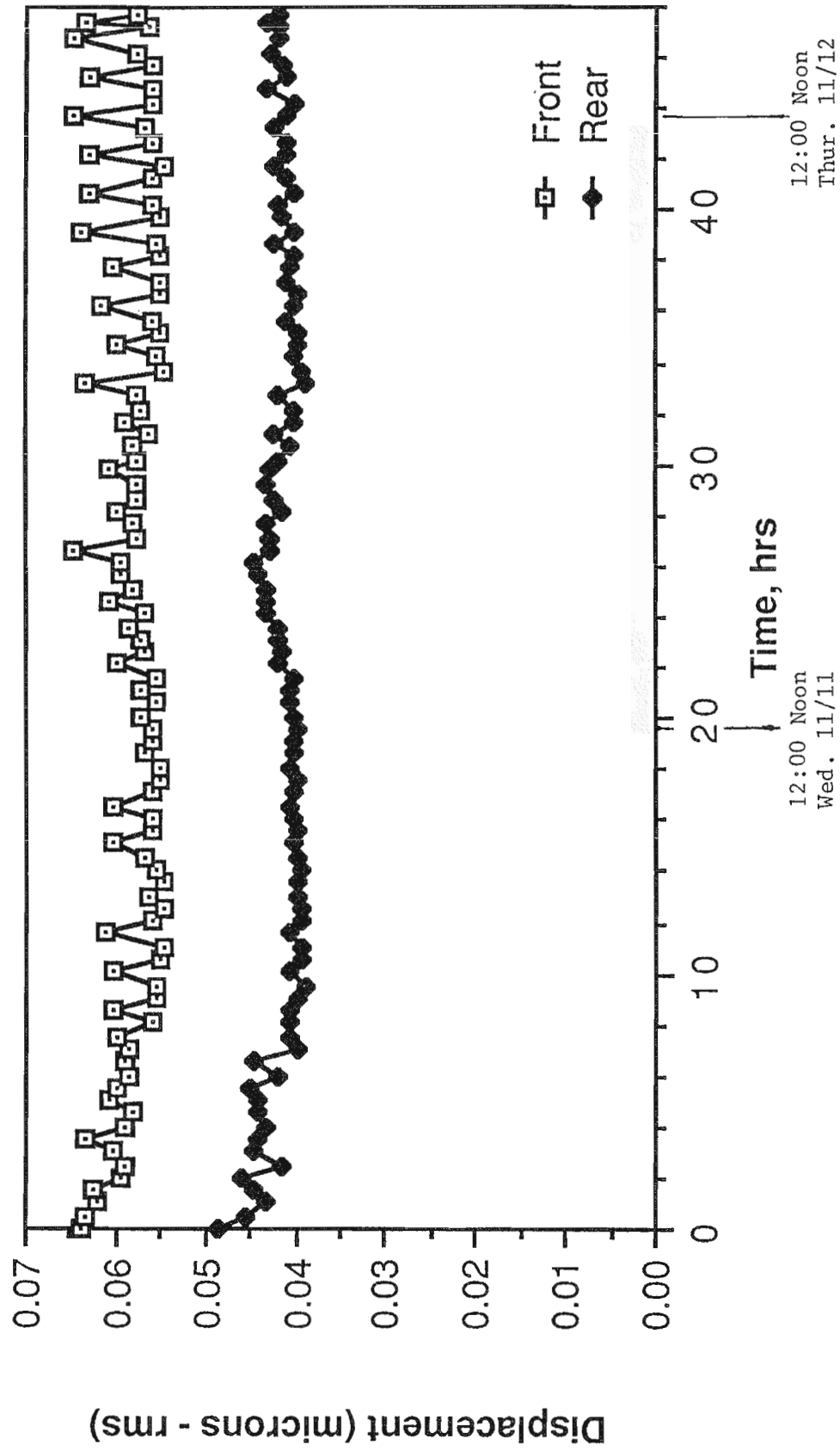


Fig. 4. Total RMS displacement-time response for active period

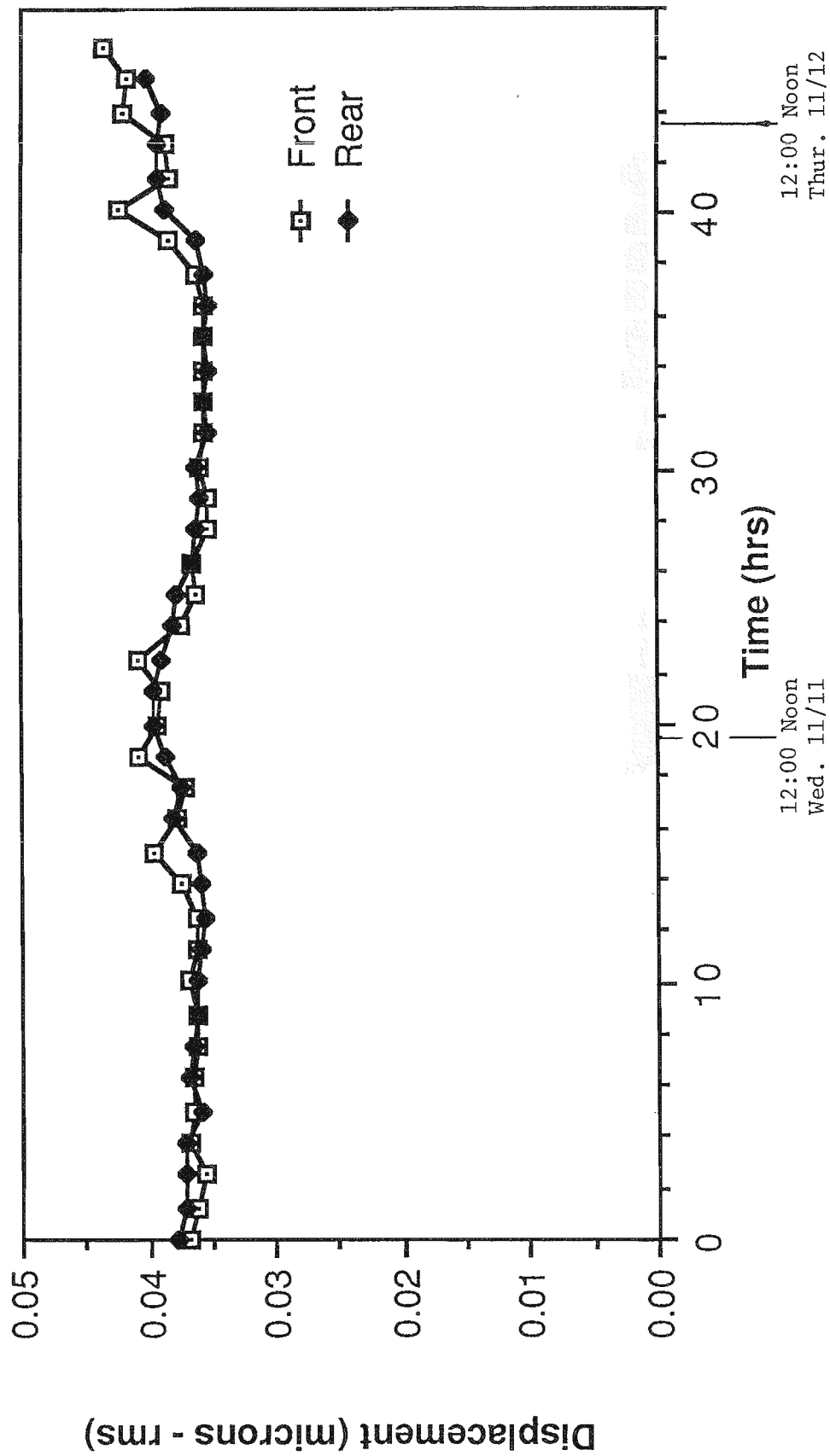


Fig. 5. RMS displacement-time response for active period, 8.1 Hz contribution removed

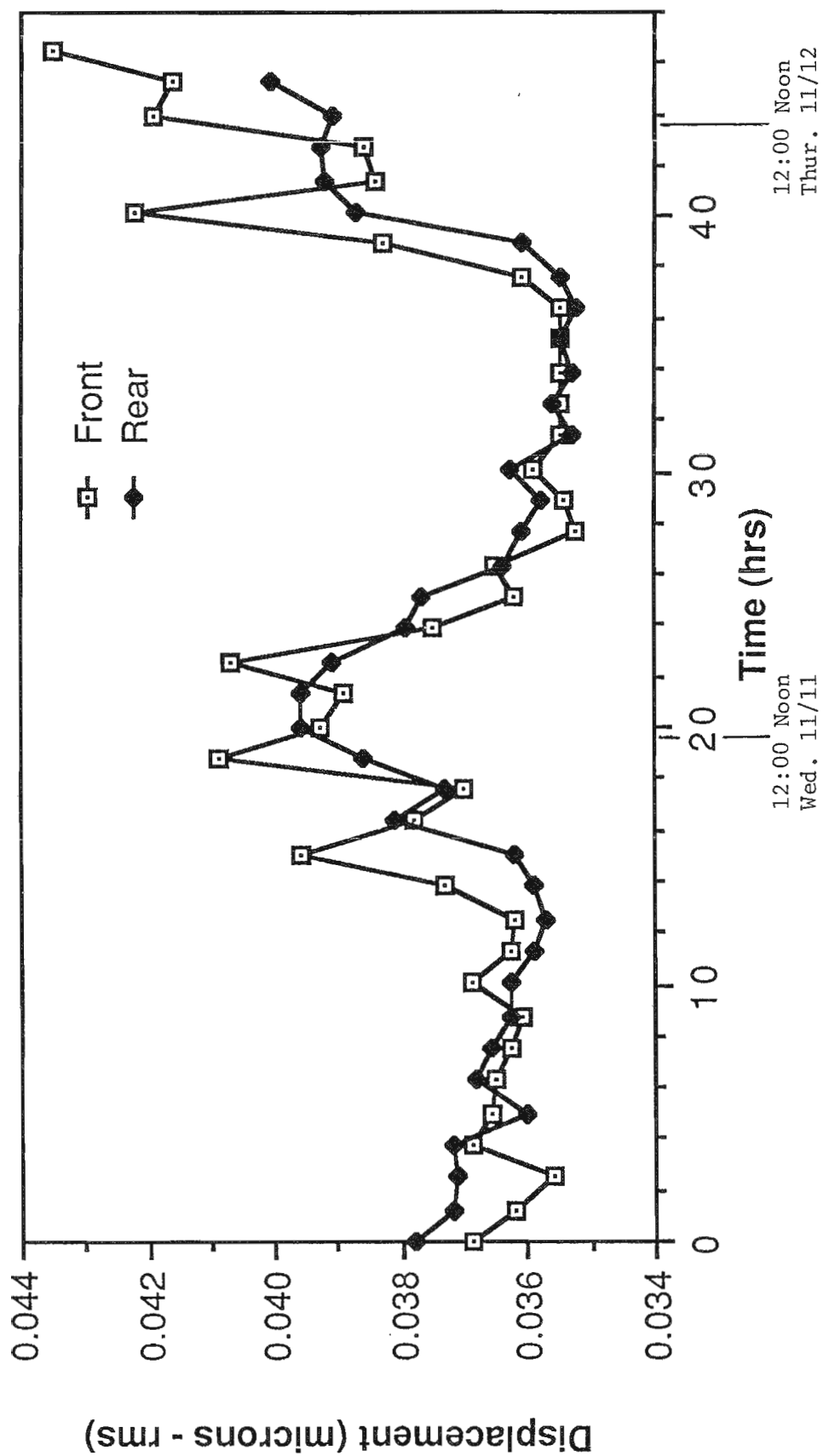


Fig. 6. RMS displacement-time response for active period, 8.1 Hz contribution removed, expanded vertical scale

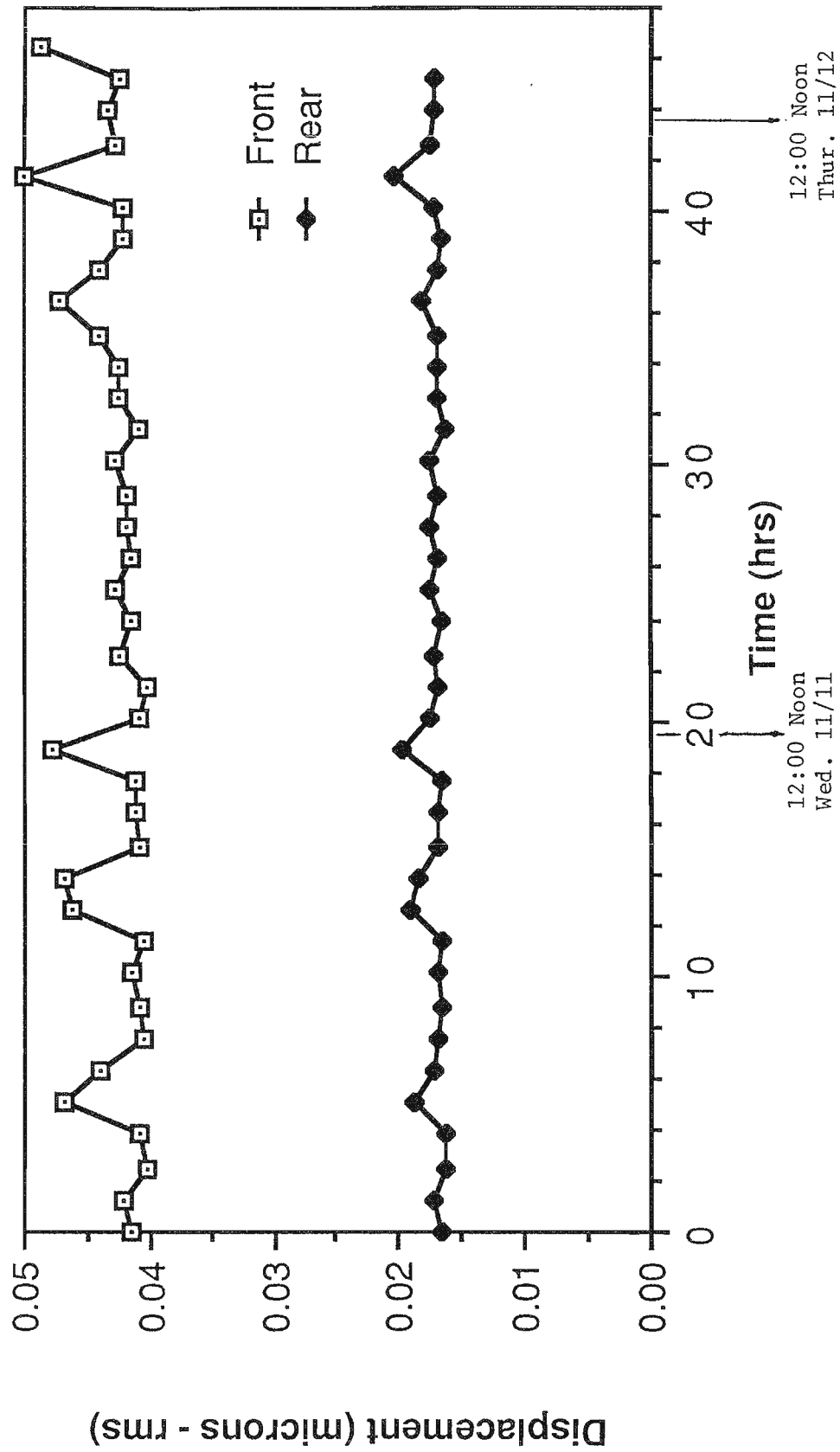


Fig. 7. RMS displacement-time response for active period, 8.1 Hz contribution

Table 2. Occurrence and Cyclic Times of Maxima
from Total RMS Displacement-Time
Response for the Active Period

<u>Occurrence Time, hrs</u>	<u>Cycle Time, hrs</u>
3.8	-
7.8	4.0
8.8	1.0
10.4	1.6
11.8	1.4
15.3	3.5
16.6	1.3
22.3	5.7
26.7	4.4
29.9	3.2
33.4	3.5
34.9	1.5
36.3	1.4
37.8	1.5
39.2	1.4
40.8	1.6
42.4	1.6
44.8	2.4
45.4	3.0
47.4	2.0

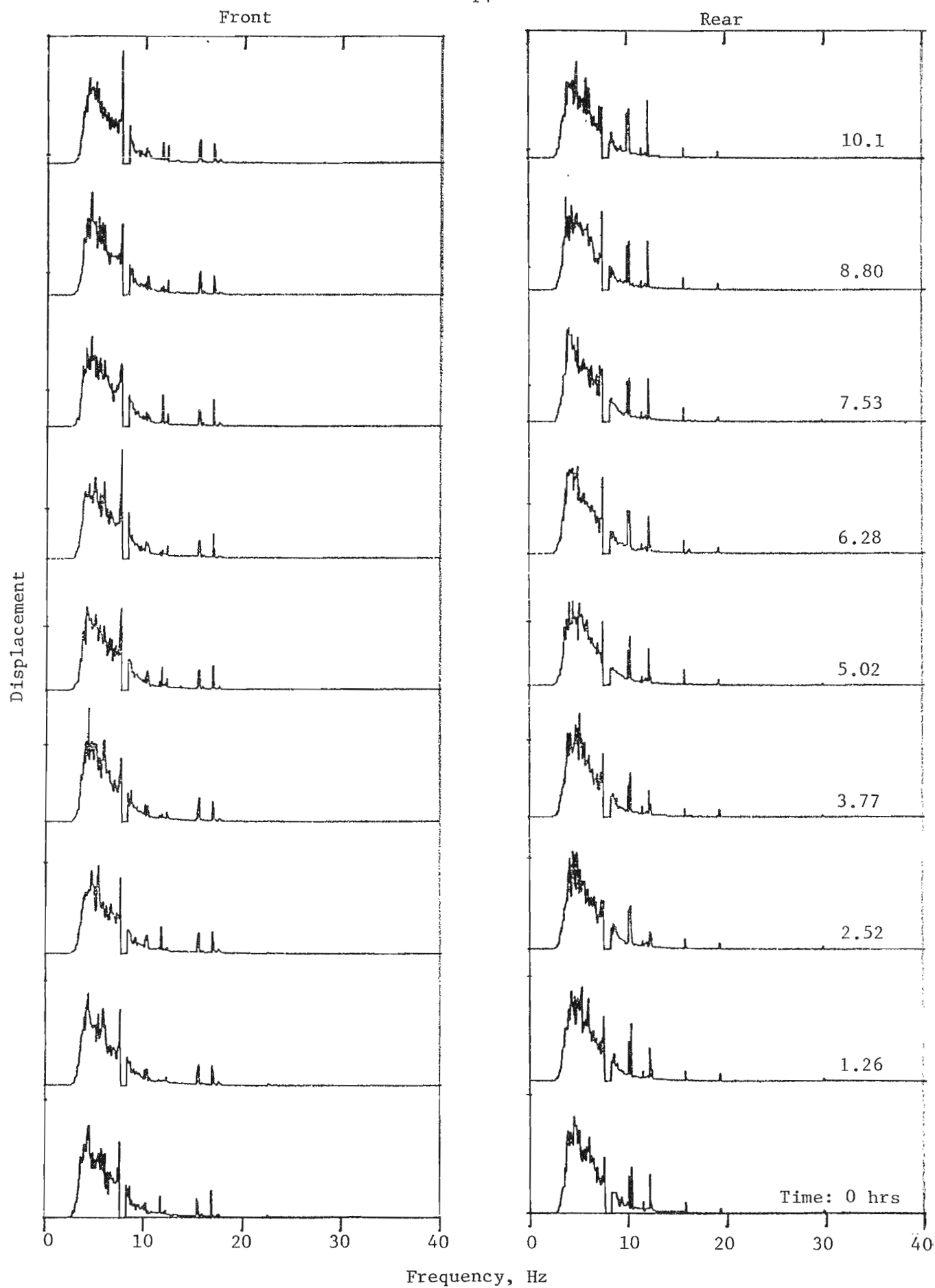


Fig. 8. Frequency content of displacement for active period, 8.1 Hz contribution removed, low site activity

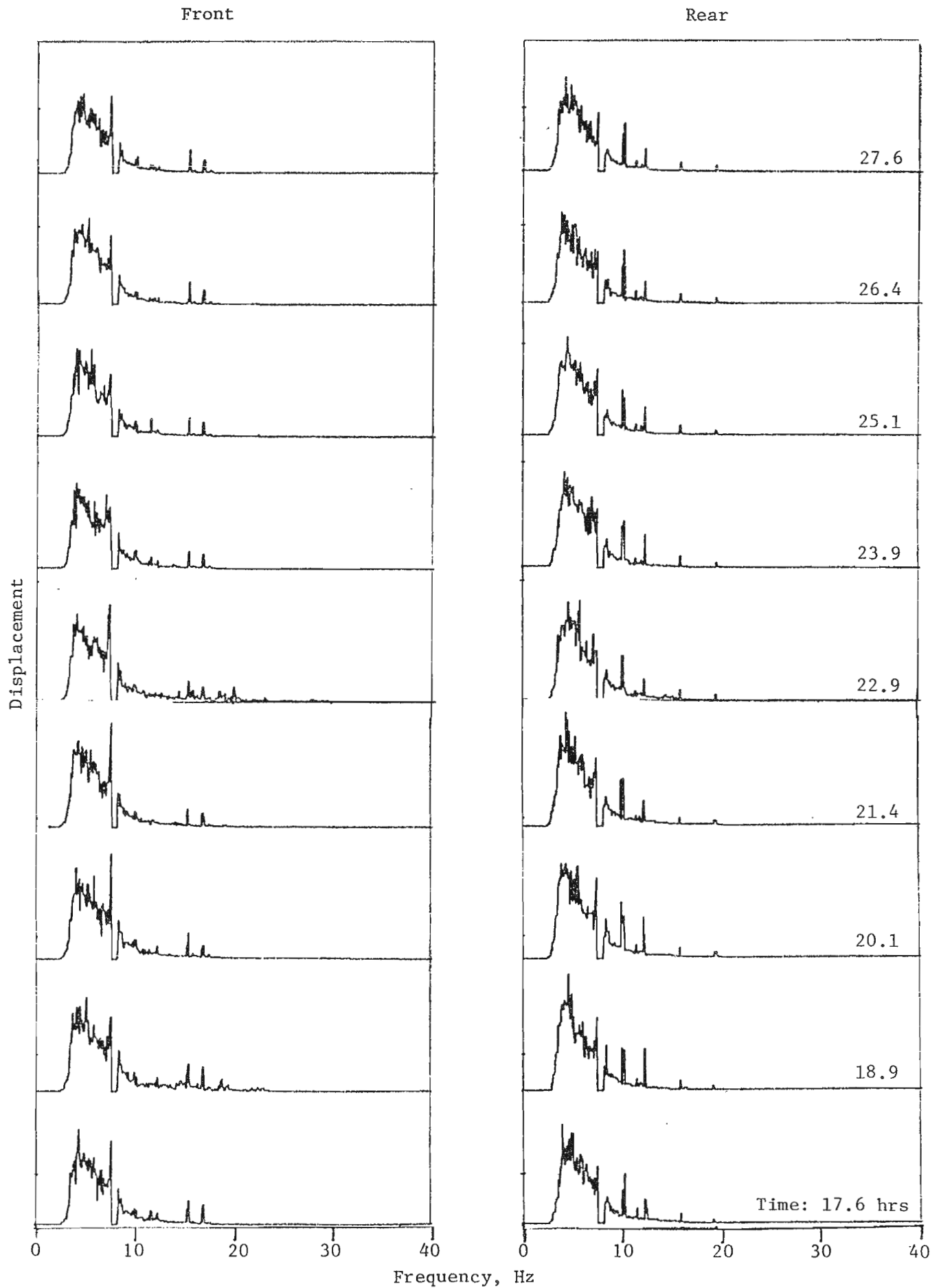


Fig. 9. Frequency content of displacement for active period, 8.1 Hz contribution removed, high site activity

frequency response is limited to 4 Hz and is the result of the low frequency cutoff filters in the double integration amplifier (PCB 180A10).

Frequency content of the "front" and "rear" displacements measured during low site activity (Fig. 8) are basically equal with the exception of some minor differences such as the 10 Hz and 12 Hz present on the "rear" PSDs and the 15 Hz and 16.5 Hz present on the "front" PSDs. The contribution to the total displacement by the above select frequencies is very small; therefore, no attempt was made to analyze them. Excluding the frequency "spikes" present, another characteristic in the response is that the displacement effectively drops to zero at about 13 Hz; any displacement above 13 Hz is below the measurement threshold and can be considered extremely small.

With regard to Fig. 9 (high site activity), the same general statements can be made about the 10 Hz, 12 Hz, 15 Hz, and 16.5 Hz frequencies as for the low site activity. However, at frequencies above 13 Hz there is more response; in particular, see plots for 18.9 and 22.9 hrs. Although the amplitude levels are low, this indicates that activity-related vibration sources can generate displacements in the 15 Hz - 30 Hz frequency range. Assuming the vibration is generated to the north of the measurement site (on or near the road) it can be transmitted significant distances (> 425 ft) as is shown in the comparison of the "front" and "rear" measurements of Fig. 9 at 22.9 hrs.

DISPLACEMENT-TIME RESPONSE - FAST CYCLE

To further investigate the cyclic nature of the 8.1 Hz excitation a series of measurements was conducted in which the spectrum of each cumulative PSD output was stored on disc as compared to one spectrum in ten on the previous data sets.

The total RMS displacement-time response is shown in Fig. 10. Amplitude levels compare well with the previous data including the decrease which was previously seen as the site activity decreases during the evening and night. Some cyclic response can be seen, but it is somewhat mixed with the random response.

Removal of the 8.1 Hz signal results in the displacement-time response of Fig. 11. Here, as in previous data, the "front" and "rear" response amplitudes are approximately equal with greater fluctuations on the "front." Spectral content of both are shown in Fig. 12. There is a small contribution to the response in the frequency range centered at 23 Hz, present on all of the "front" plots. Also there is considerably more random excitation on the "front" due to its proximity to the primary excitation sources.

The 8.1 Hz contribution is shown in Fig. 13 which highlights its cyclic nature. Again, the response compares well with the previous data with the "rear" amplitude considerably smaller than the "front." The 8.1 Hz excitation is present throughout all measurements but exhibits a cyclic increase. Table 3 displays the occurrence and cycle time in which the 8.1 Hz amplitude increases. Cycle times compare reasonably with those measured during the active period.

REAL TIME DISPLACEMENTS

In an attempt to identify the source of the 8.1 Hz excitation, the "front" displacement time signal was continuously recorded and displayed over a time span of 35 minutes. A typical response is presented in Fig. 14 which shows the buildup and decay of the 8.1 Hz excitation. The records display an interesting sequence of on-off events which are summarized in Table 4. A clear sequence of approximately 82 seconds on and 350 seconds off can be

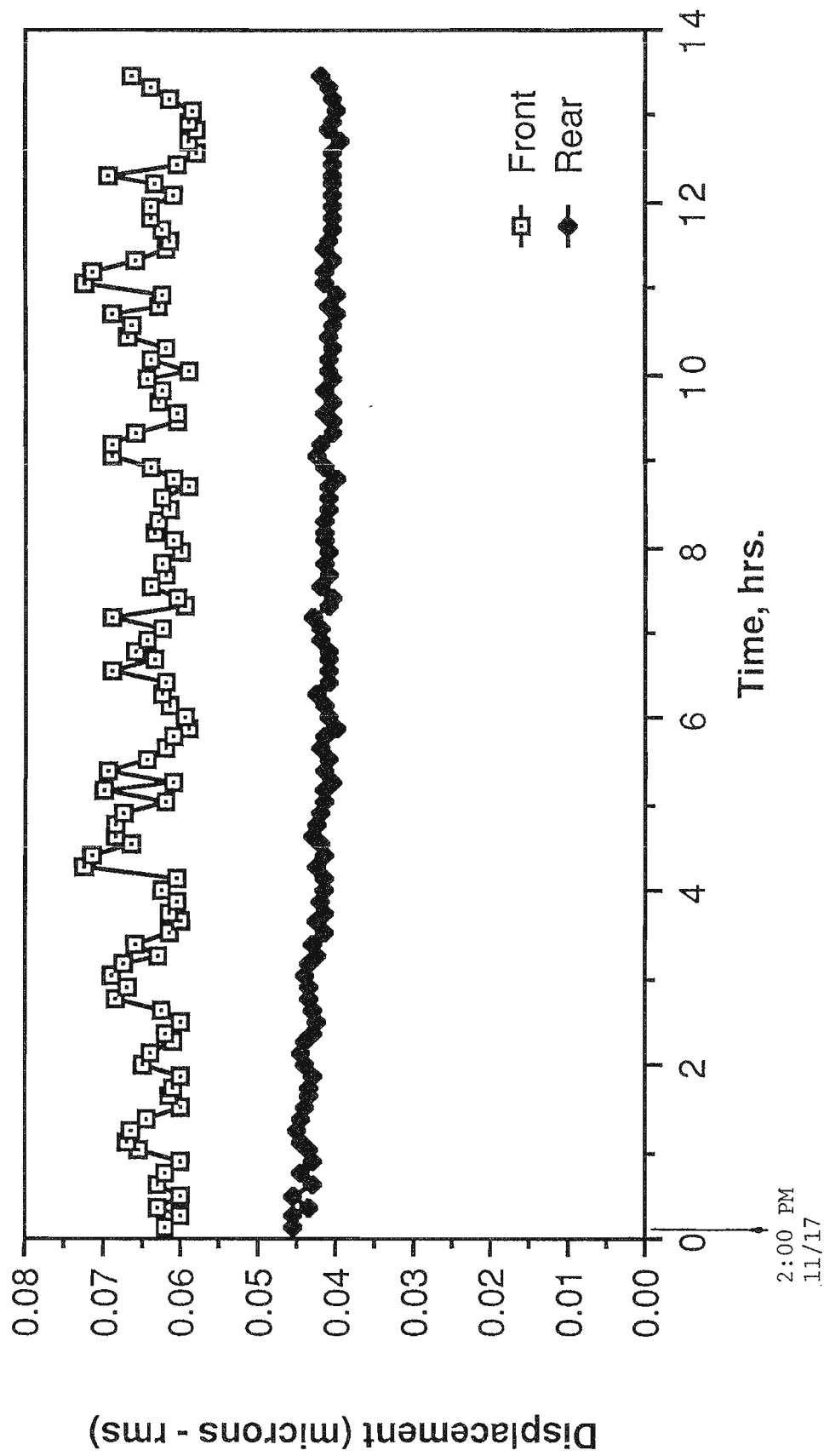


Fig. 10. Total RMS displacement-time response, fast cycle

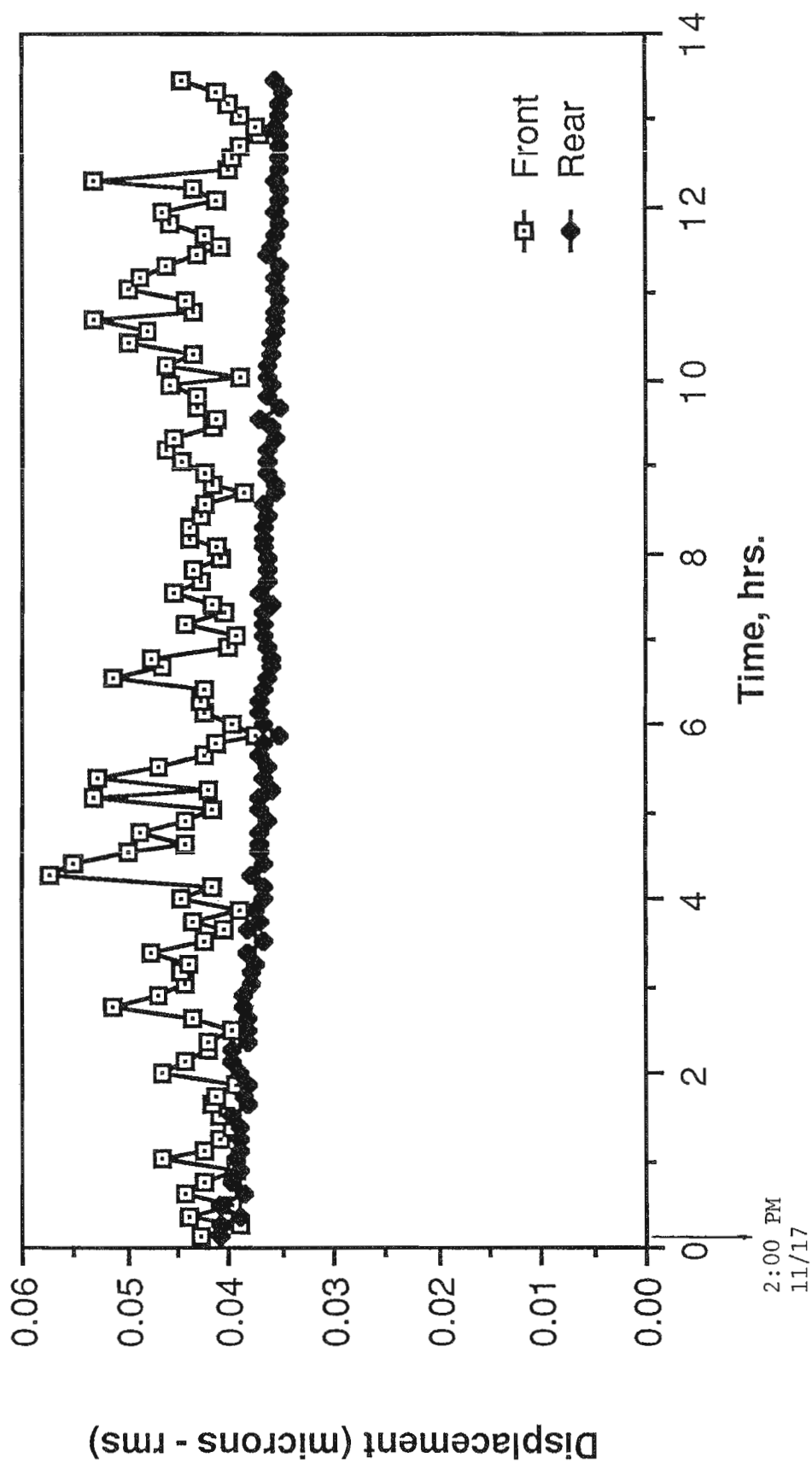


Fig. 11. RMS displacement-time response, fast cycle, 8.1 Hz contribution removed

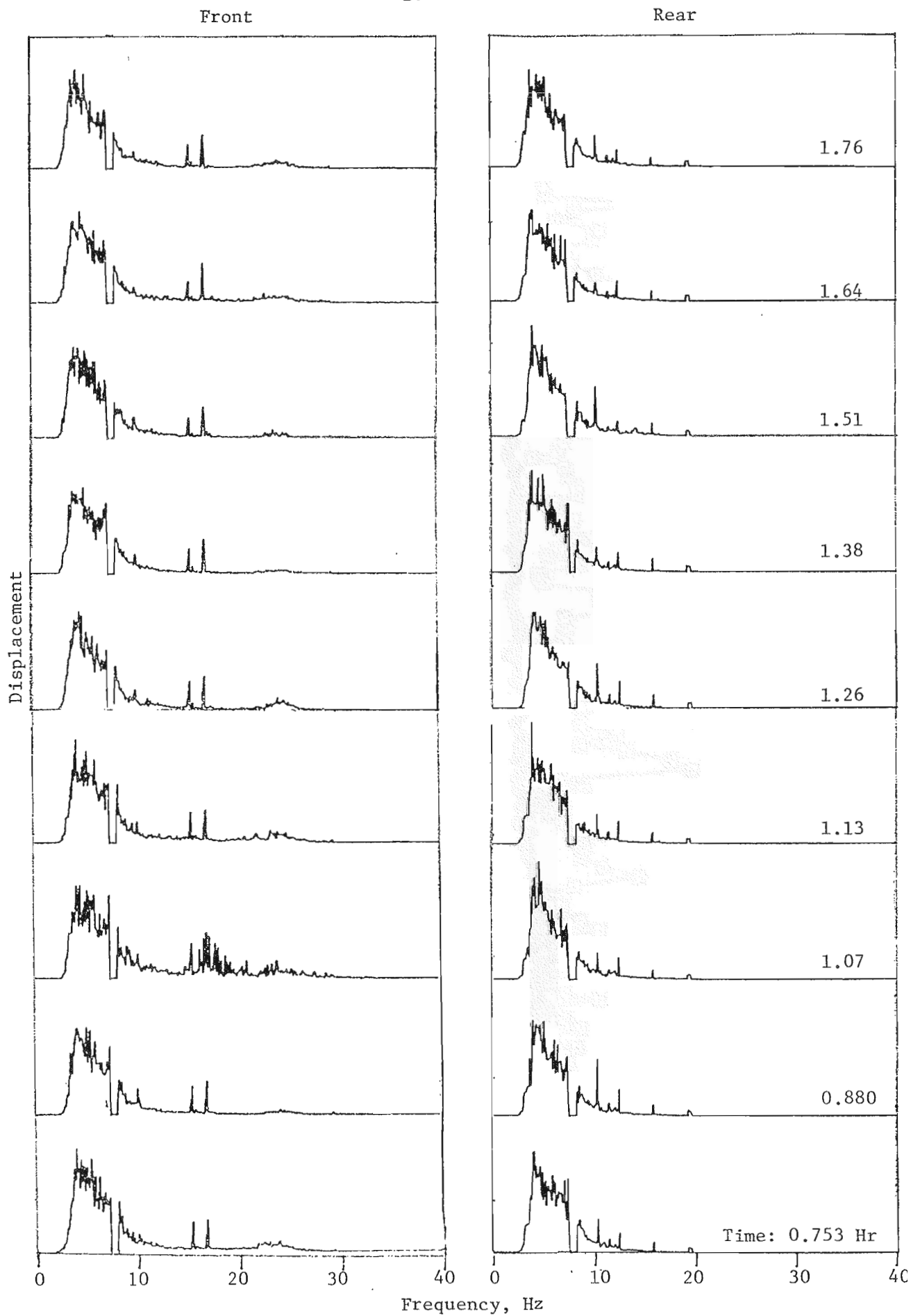


Fig. 12. Frequency content of displacement, 8.1 Hz removed, fast cycle

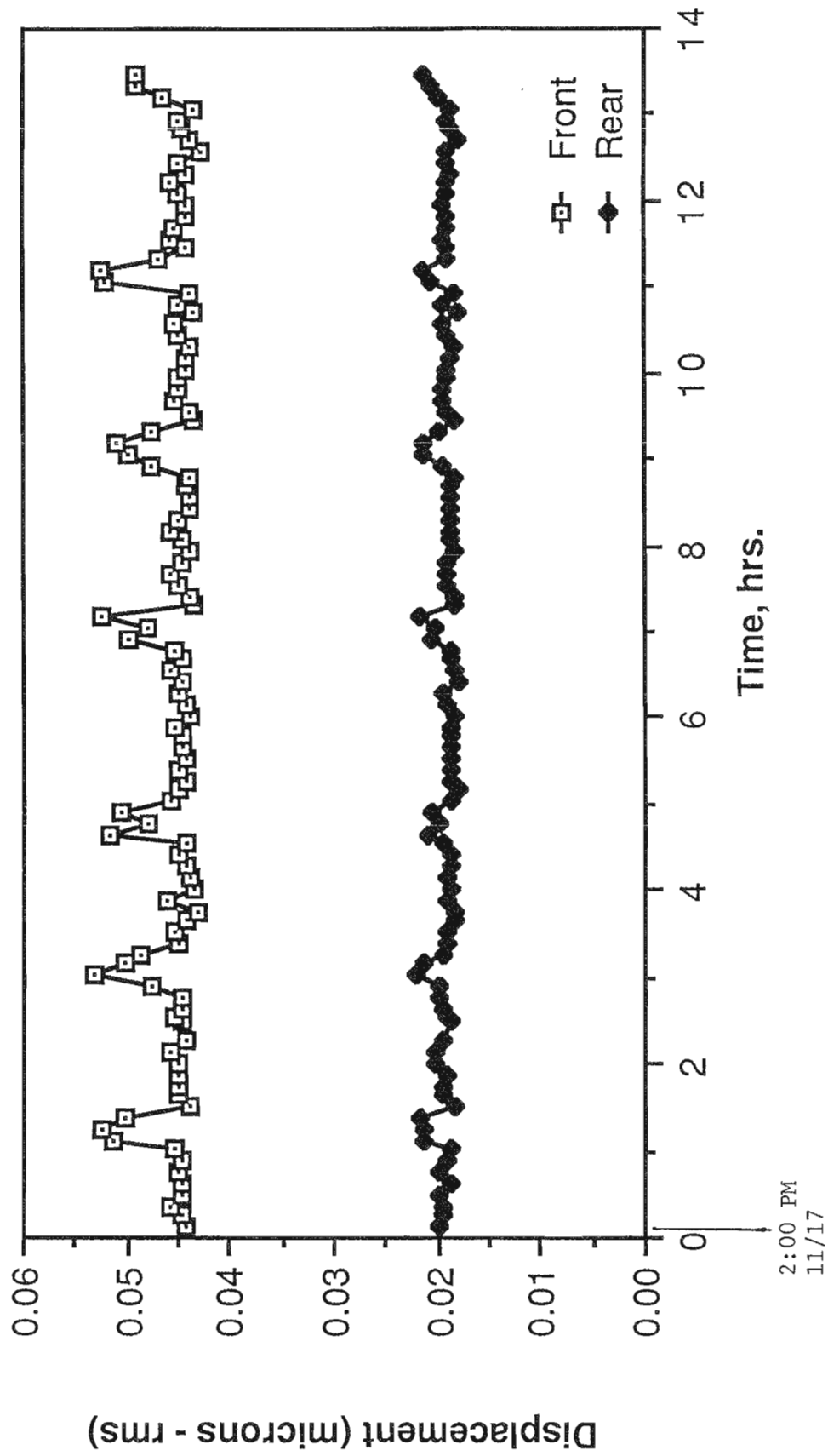


Fig. 13. RMS displacement-time response, 8.1 Hz contribution

Table 3. Occurrence and Cyclic Time of 8.1 Hz Maxima
from Fast Cycle Data

<u>Occurrence Time, hrs</u>	<u>Cycle Time, hrs</u>
1.2	-
3.1	1.9
4.8	1.7
7.1	2.3
8.15	1.05
11.2	3.05

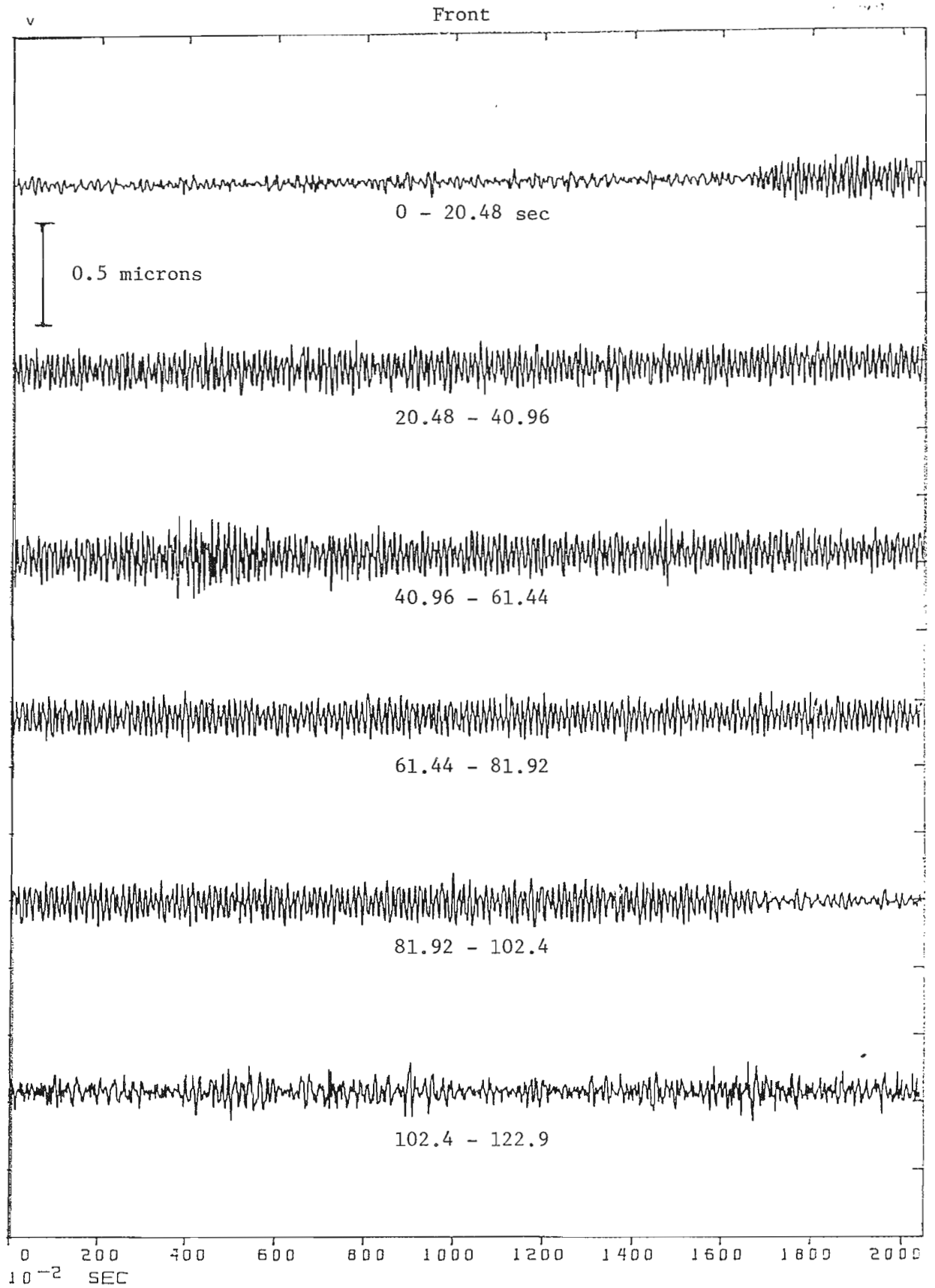


Fig. 14. Response of front transducer to 8.1 Hz

Table 4. Duration of 8.1 Hz from Measured Data

<u>Period,</u> <u>sec</u>	<u>Total Time,</u> <u>sec</u>
17 OFF	17
82.5 ON	99.5
341 OFF	441
83.5 ON	524
343.8 OFF	668
81.1 ON	949
360 OFF	1309
81.6 ON	1391
332 OFF	1723
83.8 ON	1806
341 OFF	2147

observed. From a previous study [2] it was noted that the Building 335 air compressor generated vibration at a frequency of approximately 8 Hz. The on-off sequence of the building compressor was measured and tabulated in Table 5. An on-off sequence of 101 sec on and 322 sec off is observed. Since this new sequence was measured at a later date, increased air demand would increase the on time and reduce the off time. Consequently, it is reasonable at this time to assume that the building compressor is a source of the 8.1 Hz vibrations. However, it does not explain the periodicity exhibited in Tables 1-3.

RESPONSE TO VEHICULAR TRAFFIC ON ROAD

Measurements were made to assess the ground motion resulting from vehicles traveling on Rock Road. "Front" and "rear" displacements were measured simultaneously to provide the opportunity to assess amplitude decay with distance from the source. A rectangular pulse, whose leading edge indicates the position of the approaching front of the vehicle being nearest the "front" transducer, is used to relate position to displacement. The displacement response of a medium size pickup truck traveling east is shown in Fig. 15 where a small amount of higher frequency displacement is observed on the "front" transducer. There is no indication on the "rear." Again, in Fig. 16, a very small increase in high frequency response can be observed on only the "front" with the passing of a large car traveling east. A much larger response, Fig. 17, can be seen when an 18-wheel semi tractor-trailer passed the measurement site traveling east. No indication can be observed on the "rear" transducer.

Table 5. Operation of 7.5 HP Compressor in Building 335

<u>Period, sec</u>	<u>Total Time, sec</u>
325 OFF	355
100 ON	455
320 OFF	775
100 ON	875
320 OFF	1195
103 ON	1298

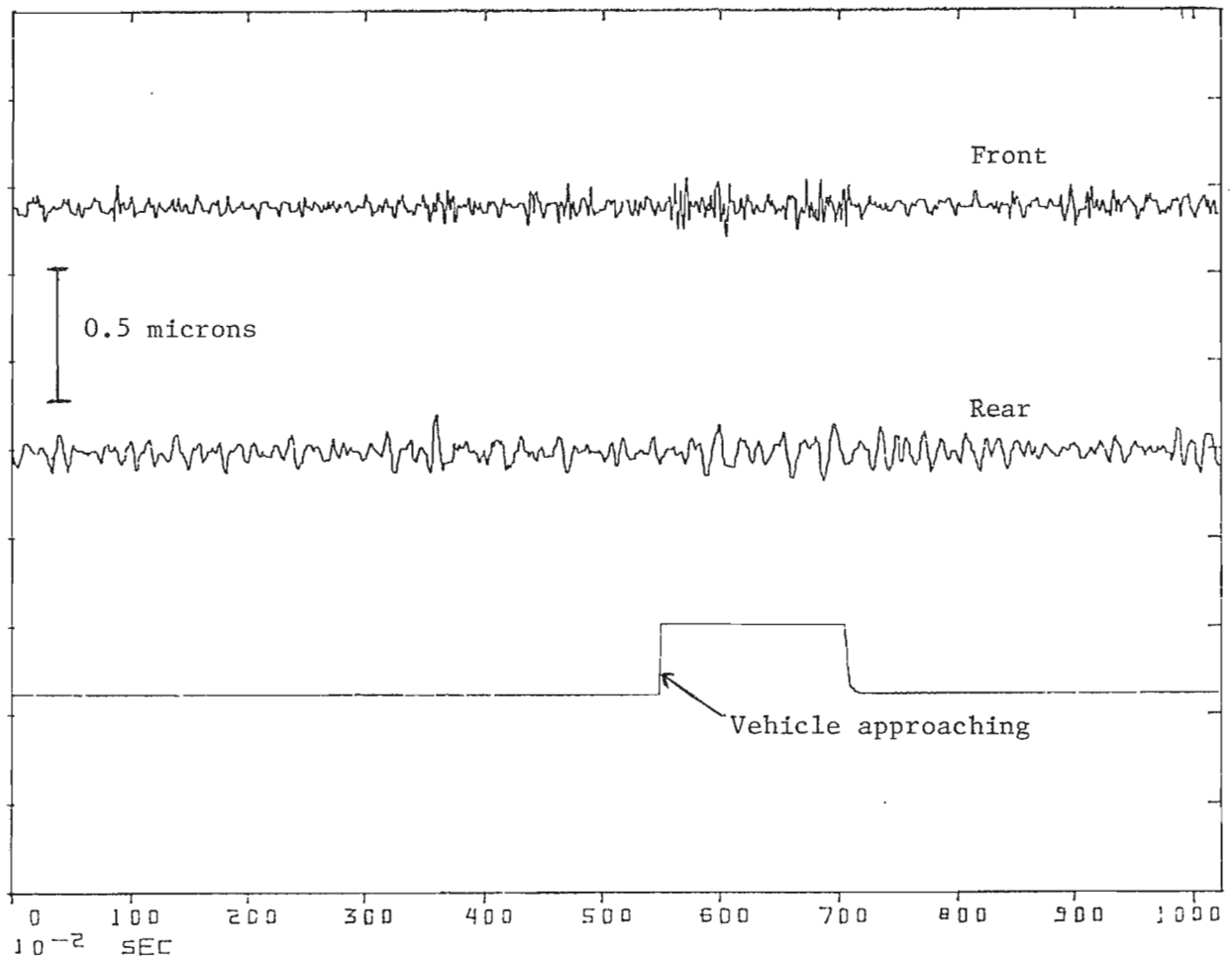


Fig. 15. Displacement response to a pickup truck traveling east

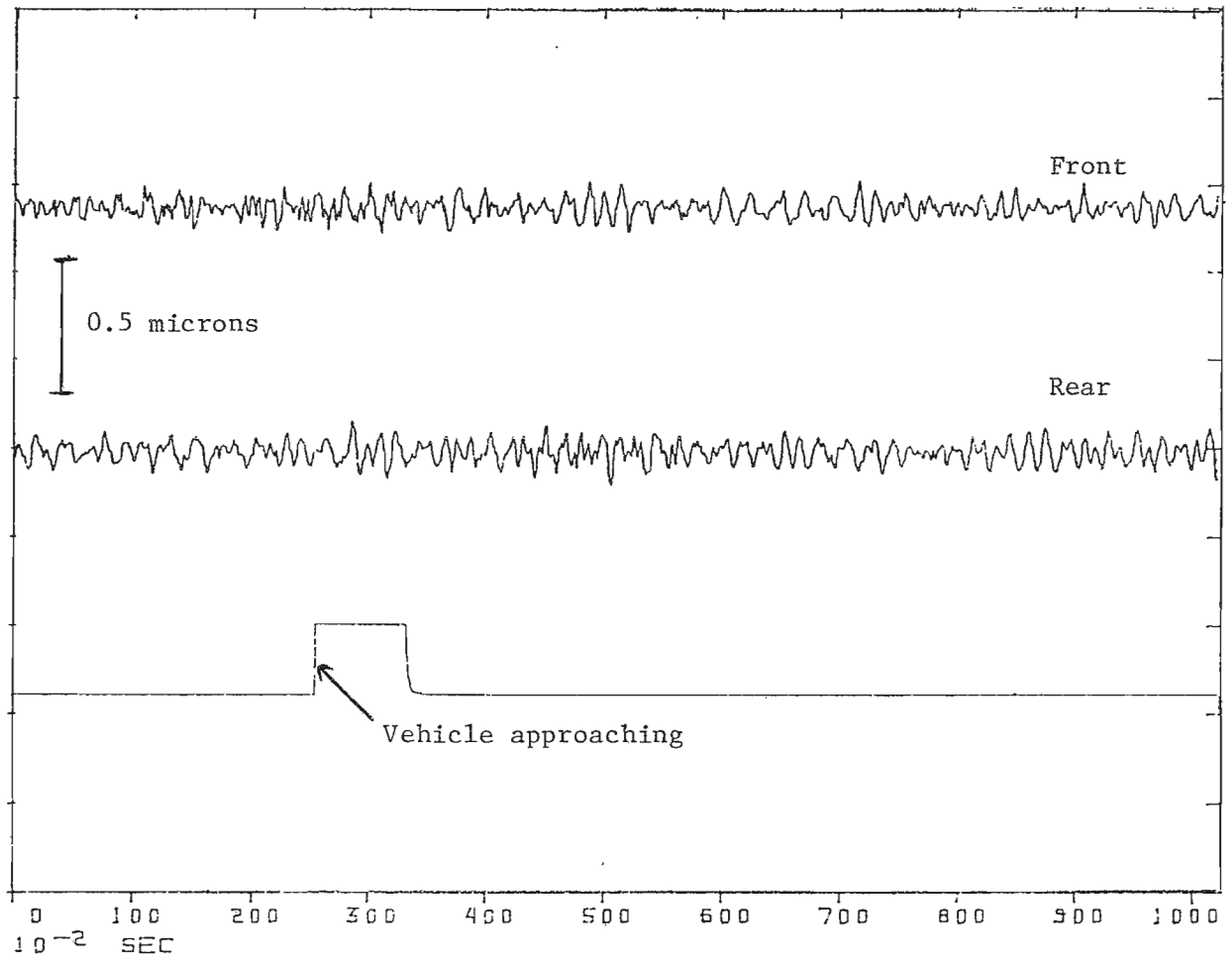


Fig. 16. Displacement response to a large car traveling east

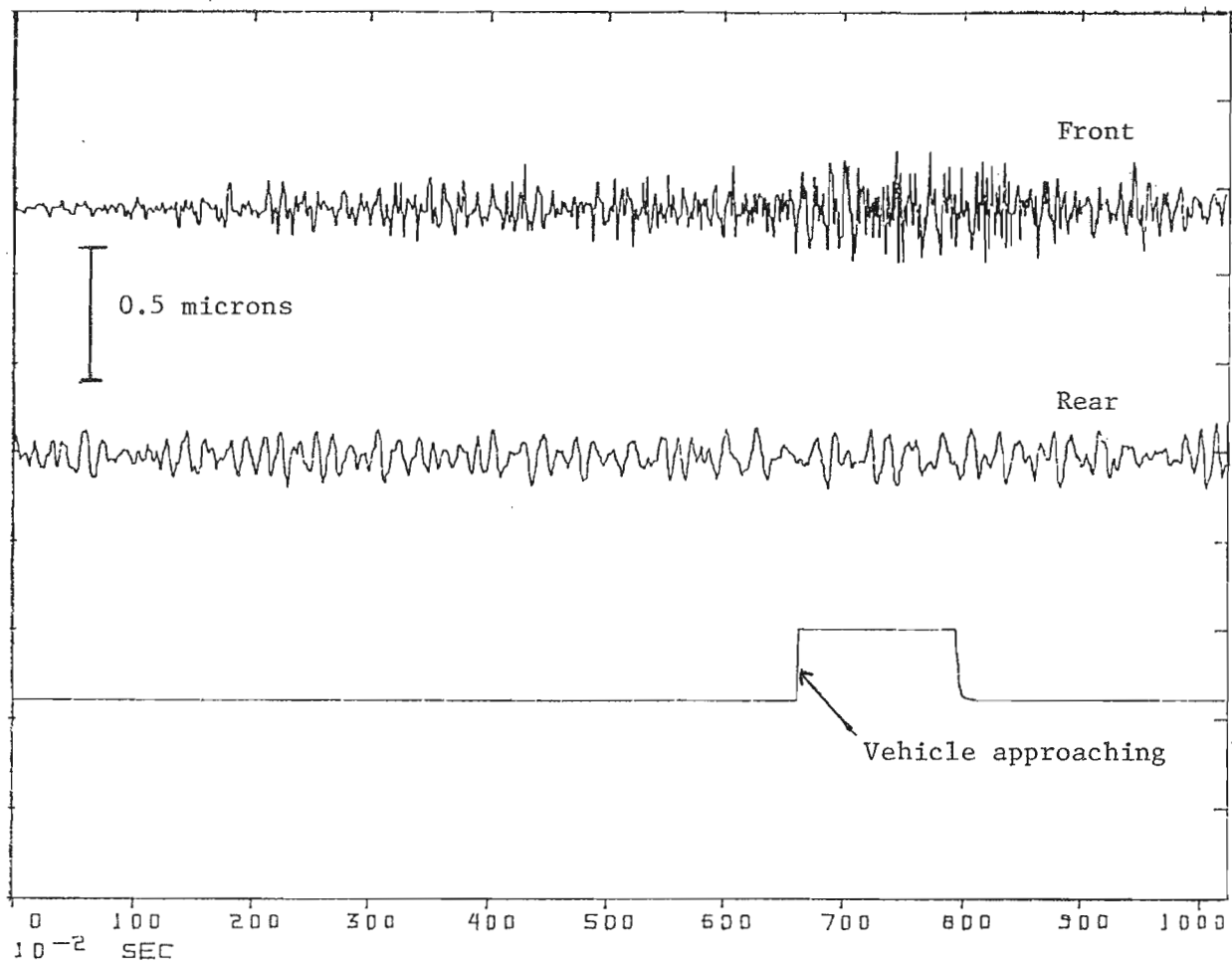


Fig. 17. Displacement response to an 18-wheel semi tractor-trailer traveling east

The above measurements are only to be considered typical of soil-vehicle response on a smooth road. Pavement discontinuities, vehicle type and condition, and vehicle speed can dramatically alter the response.

CONCLUDING REMARKS

- All measurements reported include ambient electrical noise and are conservative.
- A definite increase in vibration level correlates well to active periods at ANL.
- Excitation sources, such as compressors, can transmit vibrations considerable distances.
- Vehicles can be excitation sources. Excitation levels are functions of many variables including roughness of the road surface. While the levels measured in this study were small, it should be noted that the road is relatively smooth.
- The periodic, 1-3 hr cyclic increase in 8.1 Hz excitation could not be correlated to a known source.
- The implications relative to the APS facility are discussed below.

Limiting beam emittance growth to 10% requires that the closed-orbit displacements ($\Delta G_x, \Delta G_y$) and angles ($\Delta G'_x, \Delta G'_y$) are [3]

$$\Delta G_x < 16.1 \text{ } \mu\text{m} ; \quad \Delta G'_x < 1.2 \text{ } \mu\text{rad}$$

and

$$\Delta G_y < 4.4 \text{ } \mu\text{m} ; \quad \Delta G'_y < 0.45 \text{ } \mu\text{rad} .$$

Magnification factors between quadrupole magnet vibration and the closed-orbit distortions have been developed for various types of quadrupole motions [4].

For the worst case, random motion of all quadrupoles, the criteria for vibration amplitude to limit emittance growth to 10% are

$$(\delta_m)_H < 0.34 \text{ } \mu\text{m}$$

and

$$(\delta_m)_V < 0.12 \text{ } \mu\text{m} ,$$

where $(\delta_m)_H$ and $(\delta_m)_V$ are the horizontal and vertical components, respectively, of magnet vibration.

Neglecting the 8.1 Hz component, which has been determined to be site specific, the data in Figs. 2 and 5 indicate an rms level of $\sim 0.04 \text{ } \mu\text{m}$ for both the active and inactive periods. If we assume that the amplitudes are narrow-band random with a Gaussian, or normal, distribution, the peak amplitude can be approximated as three times the rms level. Consequently, a measured rms level of $0.04 \text{ } \mu\text{m}$ corresponds to a peak amplitude of $\sim 0.12 \text{ } \mu\text{m}$. Interestingly, this agrees with the maximum allowable vertical amplitude specified in the vibration criteria.

It should be noted, however, that magnet displacements at frequencies less than about 20 Hz can be controlled by correction magnets [3]. It can be observed from the frequency spectra in Figs. 8, 9, and 13 that the major contribution to the measured rms response is from the frequency range 0 to 20 Hz. Only the measurements made with the front accelerometer during the active period, see Figs. 9 and 12, show measurable contributions at frequencies greater than 20 Hz and those contributions are very small.

In summary, it was determined that the measured ambient ground motion occurs predominantly at low frequencies ($< 20 \text{ Hz}$) and it is known that beam displacements associated with resulting low frequency magnet vibration can be

controlled by the correction magnets. Consequently, this study supports the conclusion that the primary concern from a vibration standpoint will be internally generated vibrations transmitted through the experimental hall foundation and magnet support structures [5].

However, the study also illustrates that equipment housed in nearby buildings can be a source of measurable discrete frequency ground motion. In this case the component (8.1 Hz) was in the frequency range that can be controlled with correction magnets. Of concern is the potential for high frequency components that are above the controllable range (> 20 Hz) and which may be further magnified by the dynamics of the magnet support structures.

It is planned to supplement this study of ambient ground motion with measurements made at the APS site. As part of these measurements, vehicular traffic over a rough road will be simulated.

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